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PARAMETER ESTIMATION OF POWERED-LIFT STOL AIRCRAFT CHARACTERISTICS INCLUDING TURBULENCE AND GROUND EFFECTS

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SUMMARY

This paper considers the estimation of longitudinal aerodynamic coefficients from data recorded during flight tests of a powered-lift STOL aircraft. First, a comparison is made between the coefficient values determined by the regression and quasilinearization identification techniques from records taken during elevator pulse maneuvers. The results show that for these tests the regression method provides less scatter in coefficient estimates and provides better correlation with the predicted values. Special techniques are then developed which allow identification of the coefficients from records taken during landing maneuvers in which the aircraft encounters turbulence while flying in ground effect. Flight test results are presented to illustrate the effects of air turbulence and ground proximity on the estimated coefficient values.

NOMENCLATURE

$\dot{q}$	pitching acceleration, rad/sec^2
a_x	acceleration measured along X-axis, g units
a_z	acceleration measured along Z-axis, g units
$\bar{c}$	mean aerodynamic chord, m
C	aerodynamic coefficient
g	acceleration of gravity, m/sec^2
h	height-above-ground-level, m
I_{yy}	inertia about the Y-axis
K	constant parameter
M	aircraft weight
q	pitching rate, rad/sec
Q	dynamic pressure
S	aircraft wing area, m^2
T	thrust term
u	velocity along X-axis, m/sec
V	total velocity, m/sec
w	velocity along Z-axis, m/sec
x	vector of state variables
α	angle-of-attack, rad
δ	elevator deflection, rad
θ	pitch angle, rad
ρ	atmospheric density
σ	standard deviation (rms)
∞	free air value, out-of-ground effect
^	estimated value

1. INTRODUCTION

NASA is conducting a rather broad research program on powered-lift concepts for future use with jet STOL transport aircraft. As part of this program a C-8A Buffalo aircraft has been modified with an augmented jet-flap system (ref. 1). This aircraft has been undergoing flight tests to determine the in-flight aerodynamic performance and handling qualities. In support of this program a study has been made to evaluate the use of parameter identification techniques in determining the aerodynamic coefficient values from the recorded flight data.

Several identification methods are available from previous studies (refs. 2-10) to identify the aircraft parameters from the records taken where the aircraft is excited only by elevator inputs in calm air. These previous methods, however, are generally unable to treat the problems associated with identification of the aircraft parameters during landing maneuvers where there are significant external disturbances due to the air turbulence and ground proximity.

In this investigation two different parameter identification techniques have been applied to data recorded during pulse-type maneuvers where the aircraft dynamics are excited by elevator inputs. This paper will review the accuracy in determining the coefficient values using these different identification techniques. Special techniques are then applied to data recorded during landing maneuvers where the aircraft is excited by the combination of air turbulence, ground proximity, and the pilot's normal control actions. This paper reviews the development of these special techniques and presents results which illustrate the effects of air turbulence and ground proximity on the estimated coefficient values.

The intent of the paper is to present the genesis of each of the problems and the identification algorithms used in the problem solution along with a discussion of some of the more important findings.

2. AIRCRAFT AND INSTRUMENTATION SYSTEM

The results in this paper were obtained from flight test data recorded during test maneuvers with an augmented jet-flap STOL research aircraft (ref. 1). This vehicle (fig. 1) is a high-wing STOL aircraft powered by two turbofan engines mounted in nacelles located under the wing. The relatively cold flow from the front fans is ducted to augmentor jet flaps. The engine exhaust is directed through nozzles, one on each side of the nacelles, to provide vectored propulsive lift.

The flight test instrumentation included a nose boom with a pitot-static system and vanes, body-mounted accelerometers and rate gyros, vertical gyros, position transducers on the control surfaces, pressure and temperature transducers to measure the propulsive characteristics, and a radar altimeter to measure height-above-ground-level. The vane-measured angle-of-attack, α, has been corrected to account for angular rates and for upwash (as a function of height-above-ground). The pitching angular acceleration, a_m, has been derived from the pitch rate signal. The linear accelerations, a_z and a_x, have been obtained from the body mounted accelerometer signals and corrected (to the aircraft center-of-gravity) to account for angular accelerations. The flight data were obtained with an airborne digital recorder and then processed at discrete points, 10 points/sec, on a ground based digital computer.

3. COMPARISON OF ESTIMATION TECHNIQUES

This section will review some estimation results for standard pulse-type maneuvers in which the aircraft is relatively free from turbulence effects and is above ground proximity effects. Emphasis will be to compare results from the different identification techniques and to gain some understanding of their relative accuracy in estimating the values for the aerodynamic coefficients.

Several previous studies (refs. 2-10) have compared different identification algorithms for estimating aircraft parameters and have found that the results may depend on the technique used. These identification techniques generally fall into two categories: equation error and output error. With noise in the measured aircraft states, the equation error technique can produce biased estimates of the coefficient values (refs. 2-4). The output error technique can reduce the bias error; however, it is affected by modeling errors and also may produce the larger standard deviations in the estimated coefficient values (ref. 10). This paper will compare results of both a regression technique (equation error) and a quasilinearization technique (output error).

3.1 Identification algorithms

The non-linear equations used to mathematically model the aircraft longitudinal forces and pitching moment were taken as:

$$\hat{a}_x = (QS/M)\left[\hat{C}_{x_o} + \hat{C}_{x_\alpha}\alpha + \hat{C}_{x_\delta}\delta + \hat{C}_{x_q}(q\bar{c}/2V)\right] + T_x \qquad (1)$$

$$\hat{a}_z = (QS/M)\left[\hat{C}_{z_o} + \hat{C}_{z_\alpha}\alpha + \hat{C}_{z_\delta}\delta + \hat{C}_{z_q}(q\bar{c}/2V) + \hat{C}_{z_{C_j}}C_j\right] + T_z \qquad (2)$$

$$\hat{a}_m = (QS\bar{c}/I_{yy})\left[\hat{C}_{m_o} + \hat{C}_{m_\alpha}\alpha + \hat{C}_{m_\delta}\delta + \hat{C}_{m_q}(q\bar{c}/2V)\right] + T_m \qquad (3)$$

Coefficient terms are included which account for variations in the aircraft angle-of-attack, α; elevator deflection, δ; and pitch rate, q. This model also includes a C_z term due to the powered-lift function, C_j, (C_j = thrust of cold air/QS). Using this model the unknown coefficient values have been determined by the regression (also called equations of motion, or least squares) and the quasilinearization (also called modified Newton-Raphson) parameter identification methods. (Reference 10 outlines the details of these techniques as used for the results in this report.)

Regression is a relatively simple technique which determines the coefficient values that minimize the least squares difference between the time histories for each of the measured accelerations, a_x, a_z, and a_m, and the corresponding model outputs, $\hat{a}_x$, $\hat{a}_z$, and $\hat{a}_m$. The coefficient values are determined in three independent solutions, eqs. (1)-(3), using the well-known matrix inversion procedure (ref. 7).

Quasilinearization, in contrast to the regression method, integrates the following kinematic equations to obtain estimated time histories of the aircraft states.

$$\dot{\hat{u}} = g(\hat{a}_x - \sin\hat{\theta}) - \hat{q}\hat{w} + \hat{K}_u\,, \quad \hat{u}(o) = u_o \qquad (4)$$

$$\dot{\hat{w}} = g(\hat{a}_z + \cos\hat{\theta}) + \hat{q}\hat{u} + \hat{K}_w\,, \quad \hat{w}(o) = w_o \qquad (5)$$

$$\dot{\hat{q}} = \hat{a}_m + \hat{K}_q\,, \quad \hat{q}(o) = q_o \qquad (6)$$

$$\dot{\hat{\theta}} = \hat{q} + \hat{K}_\theta\,, \quad \hat{\theta}(o) = \theta_o \qquad (7)$$

This technique determines the coefficient values (and bias terms) that minimize the weighted least squares difference between the time histories of the measured variables, a_x, a_z, a_m, u, w, q, and θ, and their corresponding estimated values. With this technique, initial estimates for the unknown parameter values are made (e.g., from the regression results) and then the estimates are successively improved in an iterative manner, using the quasilinearization algorithm (refs. 2, 3 and 6).

One primary difference between these two methods is that with the regression method the variables, q, α, V, and Q, in eqs. (1)-(3) are taken as the measured values, whereas, with quasilinearization these variables in eqs. (1)-(3) are represented by the estimated values; $\hat{q}$, $\hat{\alpha} = \tan^{-1}(\hat{w}/\hat{u})$, $\hat{V} = \sqrt{\hat{u}^2 + \hat{w}^2}$, and $\hat{Q} = \rho\hat{V}^2/2$.

3.2 Comparison of estimated and measured time histories

Figures 2 and 3 present a comparison of measured time histories with those computed using the two identification methods. Figure 2 presents the regression results and fig. 3 presents the quasilinearization results. Values for the rms difference between the measured and estimated data are listed in table 1. Figures 2 and 3 illustrate that the estimated time histories generally fall within the scatter of the measured data. As shown in table 1, the rms fit to the pitching acceleration, a_m, is about the same for both methods; however, the regression method provides as much as a 30% better fit to the measured linear accelerations, a_x and a_z.

3.3 Comparison of coefficient values

The coefficient values determined by the two techniques are presented in fig. 4. Also shown (dotted lines) are the corresponding values which have been predicted from other independent sources, such as steady-state flight tests, wind tunnel tests, and theory (refs. 1, 11-13).

In general, the more important coefficients such as C_{z_α}, C_{x_α}, C_{m_δ}, and C_{m_q}, are in agreement both between the two methods and with the predicted values. The standard deviations (e.g., run-to-run scatter) of these estimated parameters are also relatively small.

Other coefficients, such as C_{z_δ}, C_{z_q}, C_{x_δ}, and C_{x_q}, show somewhat more scatter. The inability of either technique to estimate these terms accurately is probably because the influence of these terms on the aircraft forces is small. And also, there is a strong dependency between the elevator deflection, δ, and the pitch rate, q. Previous studies (e.g., refs. 7, 14-16) have also noted the large standard deviation associated with estimating these terms.

For almost all of the coefficients, the regression values have less run-to-run scatter and agree better with the predicted values. A majority of the regression values (with the exception noted above) are within about ±10% of the predicted values.

3.4 Discussion of identification techniques

The results presented show that the regression method provides better results than the quasilinearization method. For instance, the regression method provides a better fit to the measured accelerations, less scatter in the estimated coefficient values, and better agreement with the predicted values.

Any errors to be expected with the regression method depend, to a large extent, on the amount of measurement noise. Any noise in the measurement of the variables, q, α, V, or Q, could cause bias errors with the regression method. Although the amount of noise cannot be determined with certainty, the recorded data (e.g., fig. 3b) show very little of what may be termed white or near white measurement noise (e.g., there is a low noise-to-signal ratio). Apparently, for the flight test situations considered in this study, there are no large amounts of measurement noise that could cause significant errors with the regression method.

The errors to be expected with the quasilinearization method are related to inaccuracies in the estimates of the variables, $\hat{q}$, $\hat{\alpha}$, $\hat{V}$, and $\hat{Q}$ (fig. 3b). In particular, any modeling errors (e.g., neglect of higher-order aerodynamic terms and cross-coupling from the lateral-directional mode) will cause inaccuracies in these estimated states. Also, the quasilinearization technique usually has larger standard deviations in the estimated coefficient values because all of the coefficients are determined within one dependent set of equations, eqs. (1)-(7); whereas using the regression method, the coefficients are determined with three independent equations, eqs. (1)-(3).

For this particular application, regression appears to be the better method to use in obtaining the coefficient values. This should not imply that in other situations (i.e., where there may be larger amounts of measurement noise, or where all the states are not directly measured) regression would be the better method to use. Experience has shown that it is good practice to consider both methods utilizing, wherever possible, the advantages of each method.

4. PARAMETER IDENTIFICATION IN TURBULENCE

One of the problems in parameter identification during landing maneuvers is to account for the air turbulence which is usually present at low altitudes. Most of the previous studies have considered aircraft parameter identification in the absence of turbulence (refs. 2-10), or have made simplifying assumptions about the noise spectrum of turbulence and its interaction with the airframe (refs. 17-18). In this paper, a state estimation technique (ref. 19) is used to measure the time history of the turbulence gust disturbances. This measured turbulence is then treated as a forcing function in the aerodynamic equations. This technique makes no assumptions about the turbulence noise characteristics and further allows an examination of the manner in which the turbulence interacts with the airframe.

4.1 State estimation

The inertial velocities and position of the aircraft have been estimated by a solution of the following kinematic equations:

$$\hat{\dot{u}} = g(a_x - \sin\hat{\theta}) - q\hat{w} + \hat{K}_{u_b}\,, \qquad u(o) = \hat{K}_{u_o} \tag{8}$$

$$\hat{\dot{w}} = g(a_z + \cos\hat{\theta}) + q\hat{u} + \hat{K}_{w_b}\,, \qquad w(o) = \hat{K}_{w_o} \tag{9}$$

$$\hat{\dot{\theta}} = q \qquad\qquad + \hat{K}_{q_b}\,, \qquad \theta(o) = \hat{K}_{\theta_o} \tag{10}$$

$$\hat{\dot{h}} = \hat{u}\sin\hat{\theta} - \hat{w}\cos\hat{\theta} + \hat{K}_{h_b}\,, \qquad h(o) = \hat{K}_{h_o} \tag{11}$$

where the unknown constant ($\hat{K}$) terms are determined by quasilinearization. This application of quasilinearization requires no mathematical model of the aerodynamics; rather, the direct measurements of the accelerations, a_z and a_x, and the pitching rate, q, are used in a manner similar to that in a strapped-down inertial system (see ref. 19 for further details and the formulation including lateral motions).

For the landing approach maneuvers in this study, state estimation provides smoothing of the measured states, (h, θ), along with the estimates of the inertial velocities, $(\hat{u}, \hat{w})$, and the inertial angle-of-attack, $\hat{\alpha}_i = \tan^{-1}(\hat{w}/\hat{u})$. Figure 5 presents some of the estimated states along with the measured data for a representative landing approach maneuver. The upper portion of the figure illustrates good correlation between the radio altimeter measurement and the estimated height-above-the-runway. The lower portion of the figure compares the estimated inertial angle of-attack, $\hat{\alpha}_i$, and the airflow (vane-measured) angle-of-attack, α_a. For these representative landing approach maneuvers there seems to be a large random fluctuation of the airflow vane. The difference between the airflow and inertial angle-of-attack provides a measure of turbulence acting on the airframe.

Note: An examination has been made to determine possible errors in the airflow angle-of-attack measured by the vane. As noted previously, the airflow measurement, α_a, includes corrections for angular rate and upwash (as a function of height-above-ground). It has been found that for flight maneuvers out of turbulence there is excellent agreement between the airflow measurement, α_a, and the estimate, $\hat{\alpha}_i$.

4.2 Interaction of turbulence with the airframe

A necessary consideration in parameter estimation for STOL aircraft, traveling at low speeds, has been to determine the manner in which this measured turbulence interacts with the airframe. The turbulence as measured by the vane located forward of the aircraft will not immediately interact with the major aerodynamic surfaces. A first approximation for this delayed interaction is to use a time shift, Δt, to account for the time it takes for the measured gusts to travel from the vane until they strike the major aerodynamic surfaces.

Noting that the total angle-of-attack at any time consists of both the gust and inertial components, we have

$$\alpha(t) = \overbrace{\alpha_{gust}(t - \Delta t)}^{\substack{\text{Measured turbulence}\\ \text{shifted by } \Delta t}} + \overbrace{\hat{\alpha}_i(t)}^{\substack{\text{Inertial}\\ \text{angle-of-attack}}} \tag{12}$$

where the turbulence gust component is obtained as the difference between the measured airflow angle-of-attack and the inertial angle-of-attack at the time, $t - \Delta t$.

$$\alpha_{gust}(t - \Delta t) = \alpha_a(t - \Delta t) - \hat{\alpha}_i(t - \Delta t) \tag{13}$$

Figure 6 illustrates the effect of the time shift, Δt, on the rms fit errors, σ_{a_z}, σ_{a_x}, and σ_{a_m}, for a typical segment of a landing approach maneuver. As shown, there appears to be a different value of time shift, Δt, which will provide a minimum rms fit error to each of the measured terms, a_x, a_z, and a_m. These values of time shift appear to be reasonable from aerodynamic considerations. The fit error for the linear forces, σ_{a_z} and σ_{a_x}, are minimized if the measured turbulence is delayed by the amount of time required for the gusts to travel from the vane to near the aircraft aerodynamic center ($\Delta t = 0.4$ sec at $V = 36$ m/sec). The fit error for the moment term, σ_{a_m}, however, is minimized using the time required for the turbulence to reach the stabilizer ($\Delta t = 0.7$ sec at $V = 36$ m/sec).

The relative amounts of rms fit error reduction, with the time delay, also appear reasonable. The linear z force is strongly affected by angle-of-attack gusts and, as shown by using the appropriate time shift, the rms error, σ_{a_z}, is reduced by about 30%. The moment term and the linear x force are influenced less with a reduction of about 10% in σ_{a_m} and 5% in σ_{a_x}, by the appropriate choice of time shifts.

A further indication of the importance of time shift becomes apparent in fig. 7 where the effect of Δt on the estimate values for the coefficients, $\hat{C}_{z_\alpha}$, $\hat{C}_{z_q}$, and $\hat{C}_{z_\delta}$, is shown. Without a time shift (at $\Delta t = 0$) the estimated values are much different than predicted. However, using an appropriate time shift ($\Delta t = 0.4$ sec) these terms are near their predicted value.

4.3 Discussion of turbulence effects

The appropriate value of time shift is related to the ratio, length/speed. For the linear forces, a_z and a_x, the time shift can be taken approximately as:

$$\Delta t \approx \frac{\text{distance from vane to aircraft A.C.}}{\text{forward airspeed}}$$

For the pitching moment the time shift is approximately:

$$\Delta t \approx \frac{\text{distance from vane to stabilizer}}{\text{forward airspeed}}$$

With large STOL aircraft flying at low speeds the appropriate time delay will be in the order of seconds. For small aircraft at high speeds, however, the time delay may be quite small.

Previous parameter identification studies, which have included turbulence effects, apparently did not find a requirement to time-correlate the vane-measured turbulence. These previous studies (refs. 17-18) have considered smaller aircraft at higher speeds where the inclusion of the time shift may not be so critical. However, as shown by the results in this paper, the time-dependent interaction of turbulence on the airframe can affect significantly the estimated coefficient values and, therefore, should be considered in each application.

One additional note is that turbulence may, in fact, aid in the identification of some of the parameters. This is because turbulence acts as another forcing function in addition to the usual control input forcing function. The results from this study indicate that some of the aerodynamic coefficients may be determined more accurately from maneuvers in turbulent air (e.g., the aircraft is excited by both gusts and elevator inputs) as compared with maneuvers in clear air (excited by only elevator inputs). For instance, as noted previously, the terms $\hat{C}_{z_q}$ and $\hat{C}_{z_\delta}$ are highly correlated and difficult to determine accurately using elevator pulse maneuvers (fig. 4). However, the estimated values in turbulence are generally found to be near their predicted values (fig. 7).

5. PARAMETER IDENTIFICATION OF GROUND EFFECTS

Ground proximity effects are of concern with STOL aircraft because wind tunnel tests and theory have predicted significant changes (both static and dynamic) in the aerodynamic flow field for such high-lift aircraft near the ground (refs. 20-23). These effects on the aerodynamic coefficient values have not yet been determined by accurate in-flight measurements from landing maneuvers. This section reviews a preliminary application of parameter identification to determine the changes in the aerodynamic coefficients due to ground proximity. Parameter identification has been used in two ways. First, it has been used to determine the gross changes in the aerodynamic coefficients due to ground effect. Second, it has been used in the development of a mathematical model which indicates the amount of change in the aerodynamic coefficients as a function of height-above-ground, angle-of-attack, etc.

Representative maneuvers, which have been used to analyze the ground effects, are presented in fig. 8. In each of these runs the pilot controlled the aircraft near a constant angle-of-attack. Maneuvers are shown at different levels of angle-of-attack for different nozzle angle settings (i.e., different levels of aerodynamic and propulsive lift).

5.1 Gross effects of ground proximity

The gross effects of ground proximity on the aerodynamic coefficients can be isolated as follows:

$$\Delta C_{L_G} = C_L - [\hat{C}_{L_\infty}] \tag{14}$$

$$\Delta C_{D_G} = C_D - [\hat{C}_{D_\infty}] \tag{15}$$

$$\Delta C_{M_G} = C_M - [\hat{C}_{M_\infty}] \tag{16}$$

where the terms, ΔC_{L_G}, ΔC_{D_G}, and ΔC_{M_G}, represent the gross changes due to ground effect; the terms, C_L, C_D, and C_M, are the measured aerodynamic coefficients,

$$C_L = [-(a_z - T_z)\cos\alpha + (a_x - T_x)\sin\alpha]\,(M/QS) \tag{17}$$

$$C_D = [-(a_z - T_z)\sin\alpha - (a_x - T_x)\cos\alpha]\,(M/QS) \tag{18}$$

$$C_M = (a_m - T_m)\,(I_{yy}/QS\bar{c}) \tag{19}$$

and the terms, $[\hat{C}_{L_\infty}]$, $[\hat{C}_{D_\infty}]$, and $[\hat{C}_{M_\infty}]$ are the predicted coefficient values (total sums) derived from parameter identification out of ground effect (as discussed previously).

$$[\hat{C}_{L_\infty}] = \hat{C}_{L_0} + \hat{C}_{L_\alpha}\alpha + \hat{C}_{L_\delta}\delta + \ldots \tag{20}$$

$$[\hat{C}_{D_\infty}] = \hat{C}_{D_0} + \hat{C}_{D_\alpha}\alpha + \hat{C}_{D_\delta}\delta + \ldots \tag{21}$$

$$[\hat{C}_{M_\infty}] = \hat{C}_{m_0} + \hat{C}_{m_\alpha}\alpha + \hat{C}_{m_\delta}\delta + \ldots \tag{22}$$

Figure 9 presents representative results showing the gross changes in aerodynamic coefficients as a function of height-above-ground level. An examination of the data presented in this figure provides insight into some of the variables which influence the changes in the aerodynamic coefficients and also indicates the type of terms which must be included [illegible]he mathematical model for ground effect.

First, the magnitude of the ground effects generally vary in an exponential manner as the aircraft nears the ground. This type of variation with height is similar to that noted in most previous studies of ground effect.

Second, the ground effects vary from run to run depending upon the aircraft operating conditions. For run 1 (shown by circle symbols) there is a more positive change in lift and a more negative change in drag as compared with run 2. These differences apparently account for the greater increase in flight path angle and speed near the ground in run 1 as compared with run 2 (fig. 8). For run 1 the ground effect appears "buoyant" enough to cause the aircraft to float up away from the ground; whereas with run 2, the ground effect appears less buoyant, and the aircraft continues to descend to the ground.

Third, fig. 9 shows that the magnitude of the ground effects is somewhat different for descent and ascent (shown by the arrows). This apparent "dynamic" ground effect is illustrated in more detail with fig. 10 where the time history of ΔC_{L_G} is presented for the portion of run 1 where the aircraft descends and ascends above ground level. As shown, there is a rather abrupt loss in lift associated with the change from the descending to ascending flight path. This decrease occurs after the passage of the minimum altitude point. Apparently, the effect of the ground plane on the flow field is time-dependent. Near the ground the flow field is effectively straightened, causing a lift loss (see sketch in fig. 10). Such a lift loss, with a time lag, has been predicted from previous small scale dynamic tests (ref. 20); however, it had not yet been verified from actual flight test data.

5.2 Mathematical model for ground effect

An examination of the data presented in fig. 9 (and similar data from other runs) gives insight into the form of equations required to model mathematically the changes in the aerodynamic coefficients due to ground proximity. A preliminary mathematical model which is being evaluated is of the form

$$\begin{bmatrix} \Delta\hat{C}_{L_G} \\ \Delta\hat{C}_{D_G} \\ \Delta\hat{C}_{M_G} \end{bmatrix} = e^{-h/\hat{K}_h}\,[\hat{K}]x \qquad (23)$$

where the term $e^{-h/\hat{K}_h}$ represents the exponential variation of the ground effect with height; $[\hat{K}]$ represents a matrix (3xn) of unknown constant coefficients; and x represents a time varying vector (nx1) of state variables which influence the amount of change in the aerodynamic coefficients due to ground effect (e.g., angle-of-attack, rate of descent, etc.).

The parameter which has been found to have the most significant effect on the rms fit error is scale height parameter, $\hat{K}_h$. Figure 11 illustrates the relative rms values for C_L, C_D, and C_M as a function of $\hat{K}_h$. As shown in fig. 11, the best fit is obtained, for all three coefficients, with a scale height parameter of $\hat{K}_h \approx 4.5$ meters (15 ft).

Using the values obtained by parameter identification we can see how each of the variables (e.g., h, α, etc.) affect the aerodynamic coefficients. As an example, fig. 12 presents the estimated aerodynamic coefficients as a function of angle-of-attack both in and out of ground effect. Ground proximity is shown to cause (1) a slight increase in C_L at low angles-of-attack along with a slight decrease in the lift curves slope, C_{L_α}, (2) a reduction of about 30% in C_D, and (3) a significant shift in the moment, C_M, with an increase in the static stability, $-C_{M_\alpha}$.

The trends, due to ground proximity, found in this flight test study are in general agreement with results found in a wind tunnel study using a similar powered-lift STOL configuration. That is, the wind tunnel tests also show similar changes in lift and lift curve slope, a decrease in drag, and similar shift in moment with increased static stability. However, the magnitude of the changes are somewhat different in the flight tests as compared with the wind tunnel tests. Figure 13 compares the changes due to ground effect, ΔC_{L_G}, ΔC_{D_G}, and ΔC_{M_G}, as obtained from flight and wind tunnel tests. In comparing these data the height above the ground level has been normalized with respect to the chord length; also ΔC_{L_G} and ΔC_{D_G} are normalized with respect to their free-air values. As shown, the changes in lift and moment are in general agreement with the wind tunnel, however, the decrease in drag determined in the flight test is about three times greater than the decrease in drag determined in the wind tunnel. Some differences were to be expected between the flight and wind tunnel results because, in the wind tunnel, the angle-of-flow between the ground plane and airframe is not the same as in actual flight; and also, in the wind tunnel there is a boundary layer on the ground plane (for fixed planes), again not the same as in actual flight. Because of the difficulties of accurately duplicating the ground proximity effects (both static and dynamic) from wind tunnel tests alone, it would appear that parameter identification, as used in this study, can be an important tool in the analysis of ground effects for future vehicles.

6. CONCLUDING REMARKS

This paper has reviewed some recent flight experience in the identification of longitudinal aerodynamic coefficients for a powered-lift STOL aircraft. Comparisons were made between results obtained by the regression and quasilinearization identification techniques. Also, special techniques were presented for the identification of aerodynamic coefficients when the aircraft encounters air turbulence and ground proximity.

This study shows that for the data analyzed in this investigation the regression method provides better results than the quasilinearization method. The regression method provides a better fit to the

measured accelerations, less scatter in the estimated coefficient values, and better agreement with the predicted values.

The technique for estimating parameters in turbulence involves the use of state estimation, combined with airflow (i.e., vane) measurements, to determine the time history of the gust disturbances. The results show that the measured turbulence must be time-correlated to account for interaction of the gusts along the airframe. Using this technique, the results indicate that some of the aerodynamic coefficients may be determined more accurately from maneuvers in turbulent air (e.g., the aircraft is excited by both gusts and elevator inputs) as compared with maneuvers in clear air (excited by only elevator inputs).

In the estimation of ground proximity effects parameter identification has been used in two ways. First, it has been used to determine the gross changes in the aerodynamic coefficients due to ground effect, and second, it has been used in the development of a mathematical model for ground effect. The results show that ground proximity causes a slight increase in lift, a moderate decrease in drag, and a significant change in pitching moment.

This review illustrates that there are some differences between the results obtained by the various identification methods, but of more importance, is a determination of the form of the aerodynamic equations (i.e., number and type of nonlinear and time-dependent terms) required to model mathematically the aircraft and its interaction with external forces. For this study of STOL aircraft, during landing maneuvers in turbulence, the primary consideration has been to define the form of the mathematical models. Future work appears warranted to investigate the problems of developing the most accurate mathematical models for advanced STOL and V/STOL aircraft. The development of these mathematical models requires an analysis of the recorded flight data along with an understanding of those physical processes which may affect the vehicle dynamics.

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TABLE 1. RMS DIFFERENCE BETWEEN ESTIMATED AND MEASURED TIME HISTORIES

		Regression	Quasilinearization
σ_{a_z}	g units	0.0127	0.0176
σ_{a_x}	g units	0.00605	0.00788
σ_{a_m}	deg/sec^2	0.708	0.726
σ_u	m/sec	---	0.552
σ_w	m/sec	---	0.230
σ_q	deg/sec	---	0.295
σ_θ	deg	---	0.630

Fig. 1 Augmented jet-flap STOL research aircraft.

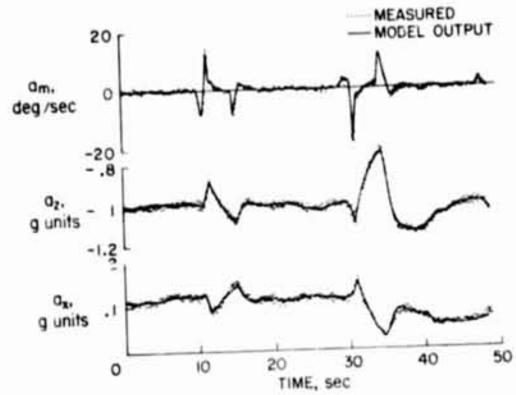
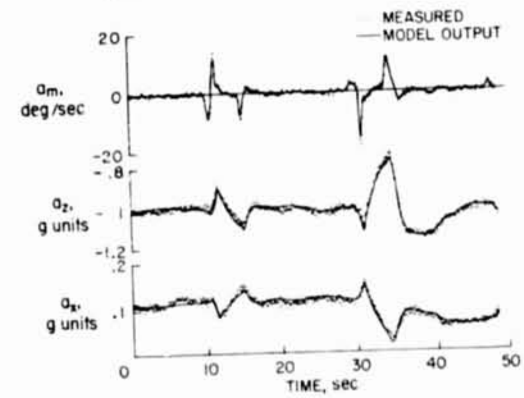
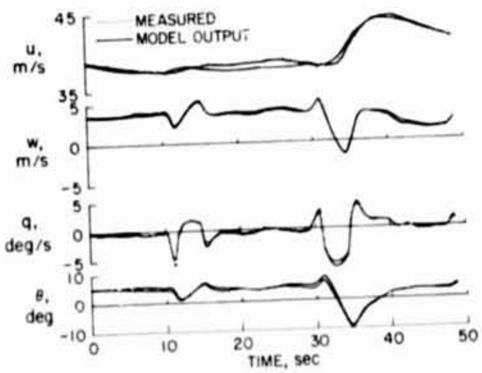


Fig. 2 Estimated model outputs compared with direct measurements; regression method.

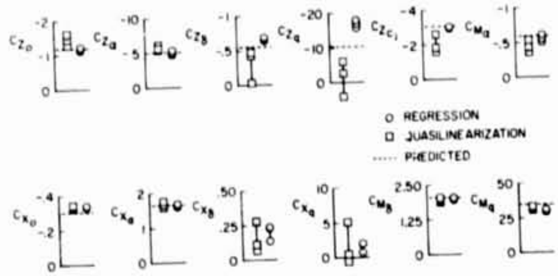


(a) Accelerations

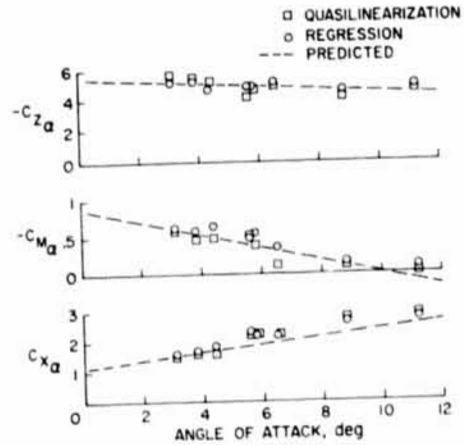


(b) Pitch angle and velocities

Fig. 3 Estimated model outputs compared with direct measurements; quasilinearization method.



(a) Three pulse maneuvers; $-2° \le \alpha \le 10°$.



(b) Variation with α.

Fig. 4 Comparison of estimated coefficient values; flap = 67°; $0.3 \le C_j \le 0.4$.

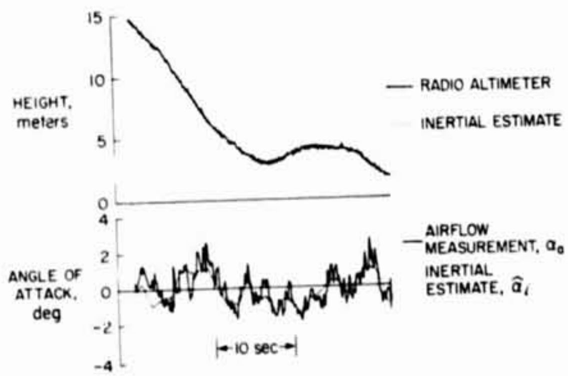


Fig. 5 Comparison of estimated states with direct measurements.

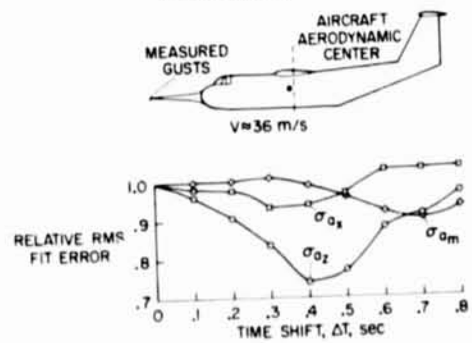


Fig. 6 Time shifting the measured turbulence to minimize the model fit error.

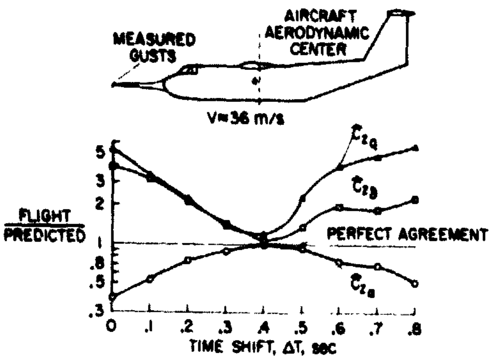


Fig. 7 Effect of time shifting the measured turbulence on the estimated coefficient values.

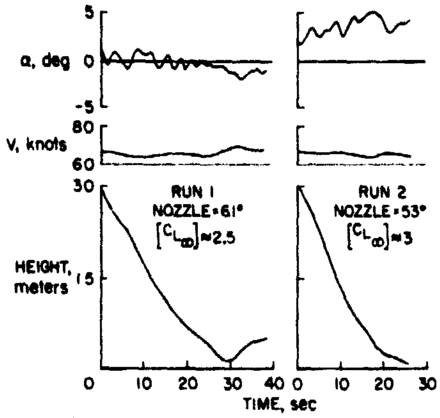


Fig. 8 Landing approach maneuvers used to determine effects of ground proximity.

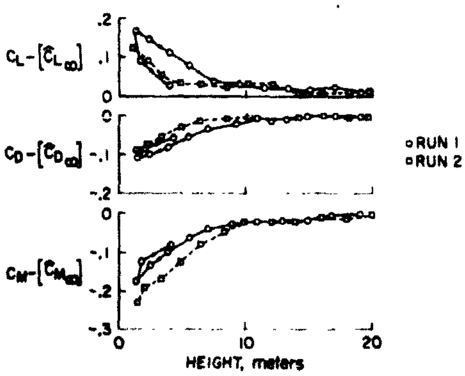


Fig. 9 Gross changes in the aerodynamic coefficients as a function of height-above-ground level.

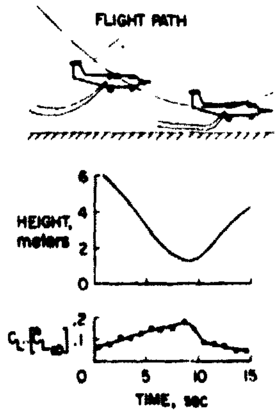


Fig. 10 The time history of changes :r lift coefficient due to ground proxim:+·.

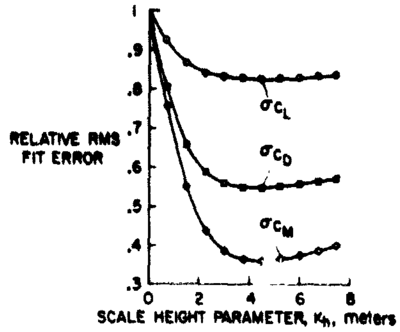


Fig. 11 Effect of the scale height parameter, K_h, on the model fit error.

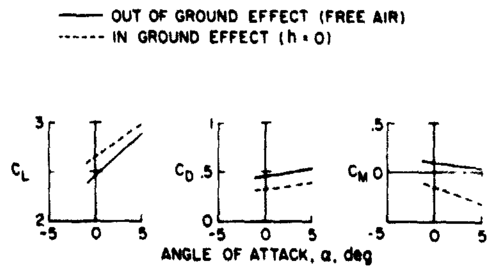


Fig. 12 Measured aerodynamic coefficients, both in and out of ground effect; flap = 67°, nozzle = 60°, C_j = 0.5.

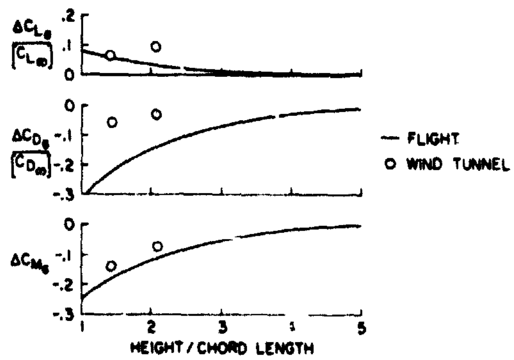


Fig. 13 Comparison of ground effect changes measured in flight and wind tunnel; C_{L_∞} = 2.5.